



# Integrating adaptive control of renewable distributed Switched Reluctance Generation and feeder protection coordination

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## ARTICLE INFO

### Article history:

Received 5 April 2017

Received in revised form 27 August 2017

Accepted 13 September 2017

### Keywords:

Wind energy

Distributed generation (DG)

Switched Reluctance Generation (SRG)

PI controller

Genetic Algorithm (GA)

Artificial Neural Network (ANN)

## ABSTRACT

This paper proposes an adaptive Proportional Integral (PI) control scheme of interconnected wind turbine-based distributed Switched Reluctance Generation (SRG). The introduced control facilitates the integration of protective relaying coordination of the distribution feeder using Artificial Neural Network (ANN). It adapts the turn-off angle of the SRG by the ANN-PI controller to regulate the injected power (and accordingly limits the injected current) from the generation unit to the network to avoid incorrect overcurrent protection coordination during grid faults. The parameters of the PI control are tuned off-line using Genetic Algorithm (GA) in order to minimize the associated Integral of Square of Error (ISE) between the reference updated power (function of the SRG voltage) and the SRG power over a wide range of abnormal grid conditions. The values of the reference updated power, the voltage level at SRG, and the corresponding optimized PI control parameters by GA are used to off-line training ANN. This proposed ANN-PI controller turns the controller into on-line one. Therefore, the proposed adaptive ANN-PI techniques could, on-line, tune the PI controller parameters for realizing an optimal response and integrating the SRG with the protection coordination by adapting the turn-off angle of SRG. By evaluating the proposed control integration with the protection coordination of an 11 kV Egyptian distribution feeder, the results provide evidences of efficient and robust performance of the proposed control for renewable distributed Switched Reluctance Generation either in steady state operation or during faults in distribution feeders.

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## 1. Introduction

Distributed generation (DG) is one of the key solutions for the emerging power supply problems. Wind power generation has become one of the most important sources of renewable energy, which demands added transmission capability and improved means of maintaining the reliability of the system. Different types of generators are used in the renewable energy systems, where most of current wind generators are with induction generators, Double Fed Induction Generators (DFIG), and Permanent Magnet Synchronous Generators (PMSG). Although the DFIG can change its operating speed and has a better utilization of wind energy, the

structure of DFIG is complex and a gearbox is required, that results in decreasing the system reliability and efficiency. The variable speed PMSG can be used directly without gearbox, but it has highly cost materials and more developments are required to enhance its performance and reliability to moderate the cost and size. The Switched Reluctance Generator (SRG) compromises several advantages compared to other types of generators such as simple and robust machine structure, convenience of control, high efficiency in a wide speed range, high fault tolerance, and high power density [1–3]. These features make it more suitable for the applications of direct-driven wind turbines.

In wind applications, energies have been carried toward the adaptation of the SRG to work with low and medium speeds that would reduce the overall cost for eliminating the gearbox. In modern studies, some techniques were proposed to avoid the influences of speed and load variation in the generated voltage using SRG [2–5]. SRG control is accomplished through the control of the switches of its converter [6,7]. However, the SRG control requirements depend on each application. The quantities for controlling

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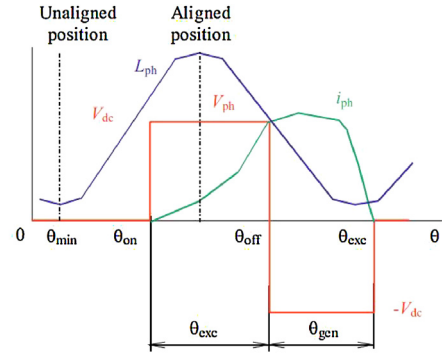
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the generation of SRG are the period of excitement, the operating speed, and excitation voltage [8]. When the load is connected directly to the converter (isolated load), it is necessary to provide a controlled voltage to the load bus. This type of control is known as SRG voltage control bus [8]. However, the power control scheme is appropriate in the grid-connected applications. In this case, the SRG is not connected directly to the grid. However, another power converter is needed for injecting the generated energy into the grid [9,10].

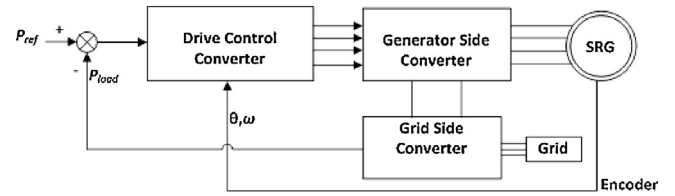
Excessive and attractive schemes of Artificial Neural Network (ANN) have been used in power system control that is difficult to be handled with classical analytical methods. In Ref. [11], the voltage and frequency control of an isolated self-excited induction generator, driven by wind turbine, is developed based on ANN approach. Static VAR Compensator (SVC) in designing isolated system based on wind energy is utilized using ANN [12]. Another ANN technique along with Genetic Algorithm (GA) is used in Ref. [13] for proper reactive compensation under different operating conditions-based FACTS devices. Also, the ANN along with GA is introduced to the problem of adaptive load frequency control as seen in Ref. [1]. However, these discussed control schemes were not applied or adapted for the renewable switch reluctance generator during abnormal conditions at its terminals especially when it is interconnected with electrical networks.

Inserting a DG into distribution feeders increases the fault currents in the grid where an additional current to the fault point is contributed by the added generator. As the network configuration is changed due to the generation interconnection, the network breakers and protection should be upgraded and updated. In order to avoid additional costs and efforts due to DG interconnection, the DG contributing currents during grid faults are limited using a fault current limiter as suggested by Refs. [14,15]. However, inserting a fault current limiter needs to add hardware devices that do not affect the current during normal operation but limit it during the fault event. Also, the optimum place of the fault current limiter for eliminating the effects of the DG on feeder protection coordination is beside the generation unit [15]. The inverter control was recently exploited to limit the fault current fed from the generator with advantages of fast limiting response and no need for further hardware implementation [16–18]. However, such a study was not investigated for the SRG-based DG which is presented and evaluated in this study.

In this paper, a new adaptive control design of the SRG connected to a distribution feeder using PI-based ANN is introduced. The PI controller parameters used for off-line training ANN are firstly optimized by GA to overcome the DG effect on the performance of protective relaying coordination during grid faults. The control scheme aims to avert increasing the current flow from the DG to grid faults by regulating the injected power from SRG by adapting the off-delay angle of the SRG. During these faulty conditions, the DG terminal voltage decreases according to the value of the fault resistance. Consequently, a new updated reference power, as a function of the DG terminal voltage during each faulty condition, is proposed. For off-line tuning of the PI control parameters using GA, several fault conditions are prepared and the optimal PI control parameters for each case are attained for the minimum value of the Integral Square of Error (ISE). On the other hand, the ANN facilitates the proposed control with adaptive features to the PI controller. Then, the PI-ANN control can be employed to the interconnected driven wind turbine-based distributed SRG to regulate the injected power from SRG to the system during faults by adapting the off-delay angle in an on-line manner. For investigation purposes, the coordination of overcurrent protection for a real Egyptian distribution feeder is evaluated when the SRG-based DG is interconnected to the grid concerning the conventional and proposed controllers. As corroborated from the results, the aimed performance is attained using the proposed controller.



a. SRG phase variables at single pulse operation.



b. Schematic of the generated power control.

Fig. 1. Power control representation of the SRG.

## 2. Proposed control integration

### 2.1. Power control of SRG

In order to operate as a generator, the machine must be excited during the decrease of inductance and a mechanical torque must be applied to the rotor of the machine [11]. There are two stages of operation of SRG namely, excitation and generation. The excitation period is between  $\theta_{on}$  and  $\theta_{off}$  as shown in Fig. 1a. In this period, the phase is excited from a DC source (or from a capacitor). In the next cycle, the generated energy of the SRG is utilized for its own excitation. In the generation period (between  $\theta_{off}$  and  $\theta_{exc}$ ) during which the electrical energy is generated and delivered to the load [13]. Therefore, the values of  $\theta_{on}$  and  $\theta_{off}$  have a great effect on the excitation and generating stages of SRG, respectively. By maintaining the value of the on-delay angle  $\theta_{on}$  at lower values, the off-delay angle  $\theta_{off}$  has an enormous effect on the output power of the SRG as illustrated in Fig. 1a.

Two converters are dedicated for controlling the power of the SRG connected to the grid. The first converter is connected to the generator (generator side converter) and it is responsible for controlling the generated power. The second converter is the DC/AC converter connected to the grid (grid side converter). This converter is responsible for adjusting the voltage  $V_{dc}$  and consequently control the power injected from the SRG to the grid. The typical power control of the SRG is shown in Fig. 1b, where the power supplied to the grid is measured and/or calculated ( $P_{load}$ ). The error between that power and the proposed reference power,  $P_{ref}$ , is used to stimulate the PI controller of the generator. The PI controller is used to drive the off-delay angle,  $\theta_{off}$ , of the generator via the generator side converter in order to reduce the injected power from the generator to the grid generated and consequently limit the DG contributing current during faulty conditions.

As discussed before, there are two SRG control strategies based on their application and the goal of using that generator. In this work, the objective of control is to regulate the power injected from the SRG to the network during fault conditions to ensure the safe operation of the generator. Moreover, the corresponding intercon-

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